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Cutting edge preparation of microdrills by shear thickening polishing for improved hole quality in electronic PCBs

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Abstract:

Printed circuit boards are representative composite material and it’s high-quality drilling machining has remained a persistent challenge in the industry. The finishing of the cutting-edge of a microdrill is crucial to its performance in machining fine quality of holes with a prolonged tool life. The miniature size involving sub-micron scale geometric dimensions, complex flute shape, and low fracture toughness makes the cutting-edge of micro-drill susceptible to breakage. Until now this has been the primary limiting factor in edge preparation for microdrills. In this paper, a newly developed cutting-edge preparation method for microdrills was tested experimentally on electronic PCBs. The proposed method namely, shear thickening polishing (STP) showed a limitation on cutting-edge burrs and tool wear, beside showing 20% enhancement in hole position accuracy, 33% reduction in nail head, and 19% reduction in hole wall roughness compared to the original micro-drill. There is however a threshold as otherwise, excessive STP results in a blunt edge, which may accelerate the wear of microdrill and have negative impact on hole quality. This study provides a new approach for high-quality manufacturing of composite PCBs materials.

Keywords:

Layered structures; Rheology; Machining; Wear

1. Introduction

Printed circuit boards (PCBs) are backbones of electronics industries [1]. PCBs is a representative composite material, serving as a substrate for interconnecting and supporting electronic components. Characterized by its multilayered structure, a PCB is typically composed of a variety of distinct materials, tailored to meet the functional and performance requirements of electronic devices. Drilling high quality holes in PCBs is a major cost in PCB manufacturing, and a single failure of the drilled hole can result in scrapping of the entire PCB. With the advent of miniaturization and current drive to make light weight parts [2,3], the margin for error has shrunk significantly [4] as well as new developments in this sector now requires to use advanced multi-layer composite materials.

Mechanical drilling is a primary hole fabrication method deployed to obtain high number of drilled holes and this method has better adaptability compared to the laser drilling method [5]. Yoon et al. [6] employed Taguchi method to investigate the impact of micro-drill geometry parameters on the PCB drilling performance. They found that helix angle and web thickness can significantly affect the wear of micro-drill. Sahoo et al. [7] employed finite element analysis to study the influence of feed rate on the quality of drilling quality, it is found that the hole diameter decreases and the mean burr thickness increases with the increase of feed rate. Bhandari et al. [8] reported a drilling burr-control chart which can aid in the prediction and control of burr formation. Zheng et al. [9,10] analyzed the interaction between the micro-drill tool and PCBs during the drilling process to elucidate the mechanisms of material removal, chip formation and wear. Lei et al. [11] used hot filament chemical vapor deposition (HFCVD) to spray nanocrystalline diamond (NCD) coatings on the micro-drill. The optimal coating location and parameters through simulation and experimentation were determined, which aided in reducing the wear of micro-drill and extended the life span.

The primary failure mechanism reported through these studies seems to be the premature wear of the cutting-edge of the micro-drill. The current another possible approach was aimed at improving the cutting-edge preparation to eliminate the sharp edges and microcracks, which could become the site of nucleation for initiation of the tool wear. It was anticipated that the elimination of micro defects would improve process reliability, reduce the wear rate and improve the hole quality in electronic PCBs [12].

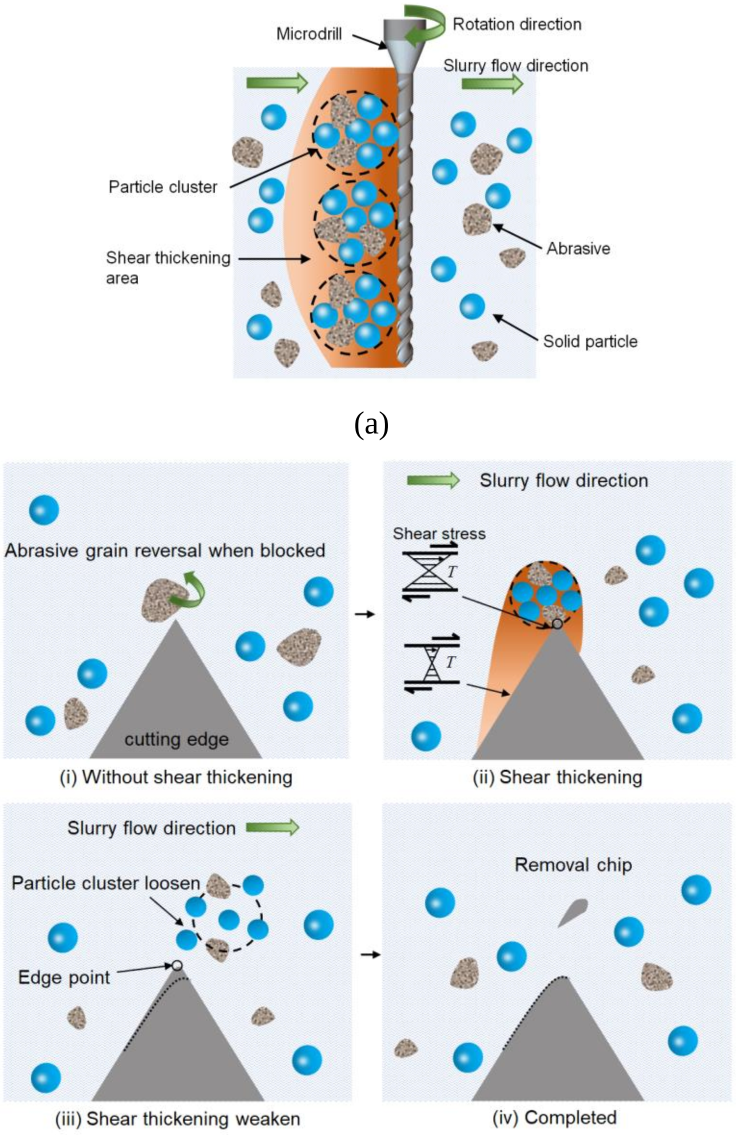
Surveying the wealth of literature on this topic, it was found that Uhlmann et al. [13,14] employed current mainstream methods for cutting-edge preparation of micro-mill with 1 mm diameter, namely brush polishing, polish blasting, magnet finishing and immersed tumbling. These methods revealed different levels of tool wear, cutting forces and surface quality through cutting experiments after edge preparation. Among these methods, the immersed tumbling method revealed lowest cutting forces, while the surface quality obtained from the magnet finishing method was the best. Nonetheless, these methods possess certain limitations, such as the exertion of substantial processing force, the presence of visible microscopic defects, and high surface roughness. In summary, the current body of literature does not encompass any reports on the cutting-edge preparation method for micro-drill with a diameter smaller than 1 mm, and the existing mainstream methods are inadequate for achieving desired cutting-edge preparation.

The shear thickening polishing (STP) method [15-17] exploits the shear thickening effect of non-Newtonian fluids to achieve efficient, high-quality and low-cost flexible polishing which is pretty useful for electronics and biomedical sector. Lyu et al. [18,19] employed the STP method to polish complex-shaped cemented carbide tools and investigated the effect of process parameters on the polishing performance, they reported a reduced surface roughness from 118 nm to 8 nm.

Span et al. [20] and Chan et al. [21] utilized a mixture of non-Newtonian fluids and abrasive particles as a processing medium. This method can be applied to prepare the cutting-edge of cutting tools with complex geometries, such as drills and mills. Shao et al. [22] performed flexible fiber assisted shear thickening polishing (FFSTP) to prepare the cutting-edge of core drill. The cutting-edge radius increased from 5 μm to 14 μm, and the highest drilling temperature was reduced by 20℃ because of the improvement of cutting-edge quality. Wang et al. [23] provides an emergent surface process technique called chemistry enhanced STP for micro-drill with complex shapes, which eliminates the burrs on cutting-edge within 3 min. The above studies indicate that STP could be potentially a very beneficial method to finish machine holes in electronic PCBs as a measure to augment sustainability by reducing the extent of electronic PCB waste. Accordingly, the work reports novel experimental findings concerning this postulation to advance the research thinking on this front.

2. Principle of cutting-edge preparation using STP

The principle of cutting-edge preparation of micro-drill by the STP method is illustrated in Fig.1 (a). During the process, the solid particles gets dispersed into deionized water to acquire the characteristics of a non-Newtonian fluid and when the abrasive particles are added into the non-Newtonian fluid, this constitutes the desirable formulation of the STP slurry. The micro-drill is then carefully inserted in the polishing slurry to a fixed depth and rotating to make the polish more even. The polishing slurry flow through the micro-drill, the shear thickening occurs when the shear stress exceeds a threshold, and the solid particles form particle clusters while encasing the abrasive particles in the shear thickening area. At the same time, the viscosity of the polishing slurry increases. The polishing slurry transforms from a fluid to a solid-like state, forming a 'flexible conformal abrasive tool' that matches to the complex micro-drill and moves around to contribute to the material removal process.



(a)

(b)

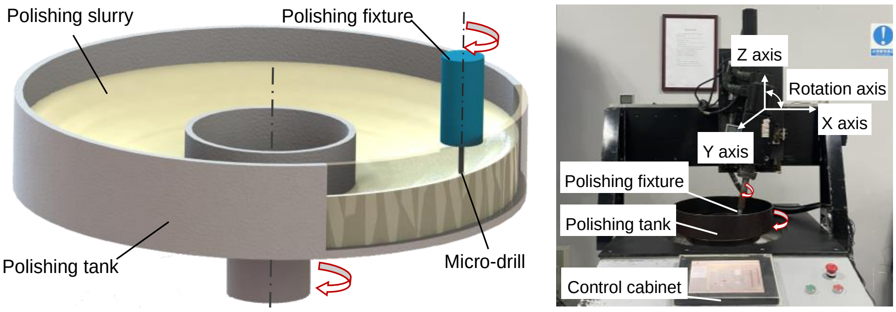
Fig.1 Schematic illustration of cutting-edge preparation by the STP method

The process of material removal mechanism involved in the smoothening of cutting-edge is schematically shown in Fig.1 (b). In the first stage, when the shear stress is below the threshold, the shear thickening phenomenon does not occur and the abrasive particles are blocked and reversed when passing through the cutting-edge. Hence, the abrasive particles have almost no material removal effect on the cutting-edge. In the second stage, as the shear thickening occurs, the particle clusters carry the abrasive through the cutting-edge to remove the material. The shear stress near the edge point is the highest, gradually decreasing with the edge face. Therefore, the material is removed fastest at the edge point. In the third stage, the "particle clusters" experience a reduction in shear stress at this region after passing through the cutting edge of the tool. So the gradual reversion of the "particle clusters" to a loose state. Solid-phase particles and abrasive grains disperse back into the polishing slurry in a random manner. In finally, after a certain period of STP process, the material from the cutting-edge gets removed, making a sharp cutting-edge to have certain radius. Depending on the duration of the STP process, this radius can be controlled and a micro-drill with a deterministic cutting-edge radius can be obtained.

3. Experimental methodology

3.1 Cutting-edge preparation of micro-drill

The experimental campaign began with the sourcing of consumable items. Cemented carbide micro-drills with a diameter of 0.4 mm containing 94 wt.% tungsten carbide and cobalt binder were sourced from Shenzhen Jinzhou Precision Technology Co., China. The micro-drills were subjected to the STP process using the experimental apparatus shown in Fig.2. To do so, the micro-drill was clamped on the polishing fixture and immersed into the polishing slurry. The polishing slurry was fed from the polishing tank while the micro-drill and the fixture spun. The starting parameters were taken from the literature [18,19,24] but fine-tuned according to the properties of the micro-drill. The detailed experimental parameters are shown in Table 1. During experiments, the processing time was changed to obtain different edge radii of the cutting-edge.



(a) (b)

Fig.2 (a) Schematic illustration of cutting-edge preparation by STP, (b) Illustration of the STP apparatus

Table 1 Experimental parameters

Processing conditions	Parameters
Abrasive	Diamond
Abrasive size	Average 2.5 μm
Abrasive concentration	10 wt.%
Depth of immersion	4 mm
Polishing speed	1.3 m/s
Workpiece rotation speed	10 rpm
Polishing time per trial	Trial I: 0 mins (without STP process) Trial II: 5 mins Trial III: 10 mins Trial IV: 15 mins

After polishing, the topography of flank face and major cutting-edge were imaged by a light microscope (VHX7000, Keyence, Japan) and SEM (SIGAM HV, Carl Zeiss, Germany). The 3D profile of the major cutting-edge was scanned by a three-dimensional optical microscope (Infinite Focus G5, Alicona, Austria), and 50 cross-sections were obtained from the 3D profile. The software provided by the equipment was used to analyze blunt radius of the major cutting-edge to obtain the average value of the edge radius.

3.2 Drilling experiments

As shown in Fig.3, the drilling experiments were performed on a drilling machining (ND-6N210E, Hitachi, Japan) with electronic PCB workpiece (EM 370D, Elite Material Co., Ltd., China). The detailed processing parameters used for the micro-drilling experiments are presented in Table 2. These optimal parameters were provided by the vendor Shenzhen Jinzhou Precision Technology. A total of 2000 holes were processed, with each hole spaced 0.5mm apart. And each group of experiments was performed at least three times to ensure reproducibility and accuracy of the results. After micro drilling, a digital microscope (DSX510, Olympus, Japan) was used to measure the unworn area on the flank face of the micro-drill to evaluate the wear of the drill as per the suggestion made in the literature [27,28].

A Hole-AOI/Express system (Hole-AOI, Machvision, Taiwan) was used to assess the accuracy of hole position, and the results were expressed with respect to the process capability index (CPK). Post-drilling examination involved careful preparation of the hole slices which were objectively inspected for the nail head and hole wall roughness using a metallographic microscope (DM2700M, Leica, Germany).

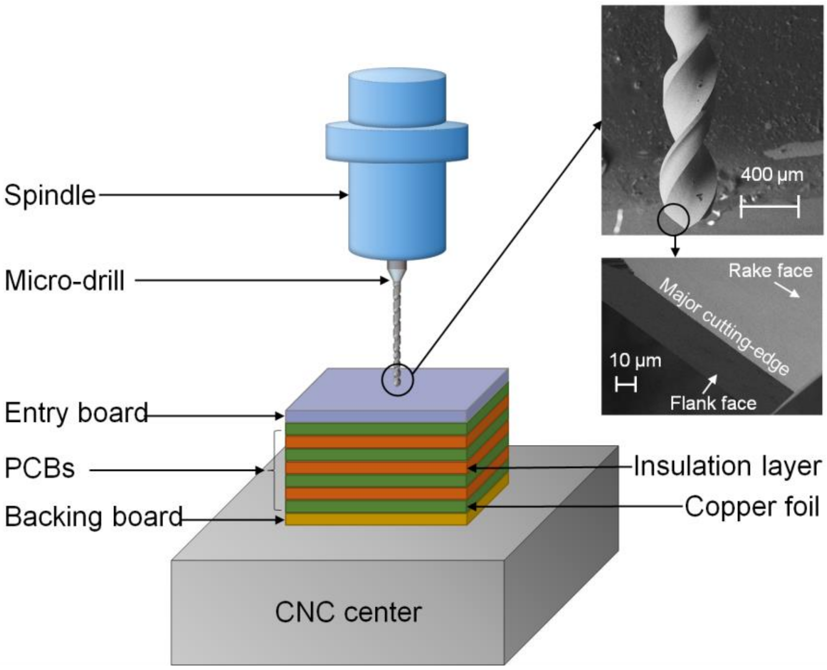


Fig.3 Schematic of micro drilling system for processing the electronic PCB 04

Table 2 Drilling parameters used during the experiments.

Parameters	Values
Spindle speed	115 Krpm
Feed rate	35 mm/s
Retraction speed	300 mm/s
Entry board used	Aluminum sheet
Backing board	Phenolic resin
Stack of board layers	3
Number of holes drilled	2000

4. Results and discussion

4.1 Micro-drill edge characterization

To accurately estimate the bluntness of the cutting-edge, the radius of the major cutting-edge was measured which is shown in Fig.4. In trial I (original micro-drill), the initial radius of the major cutting-edge was approximately 3.2 μm. And the radius increases linearly with duration of STP. For instance, in trial II (process 5 mins), trial III (process 10 mins) and trial IV (process 15 mins) the edge radius of the cutting-edge becomes about 3.8 μm, 4.9 μm, 5.6 μm, respectively.

The major cutting-edge topography of micro-drill after STP at different times is also shown in Fig.4. In trial I, the grinding marks near the major cutting-edge form burrs and chippings. After STP processing, a smooth transitional region appears on the cutting-edge surface in trial II. The major cutting-edge becomes blunt, and burrs are entirely removed in trial III and IV.

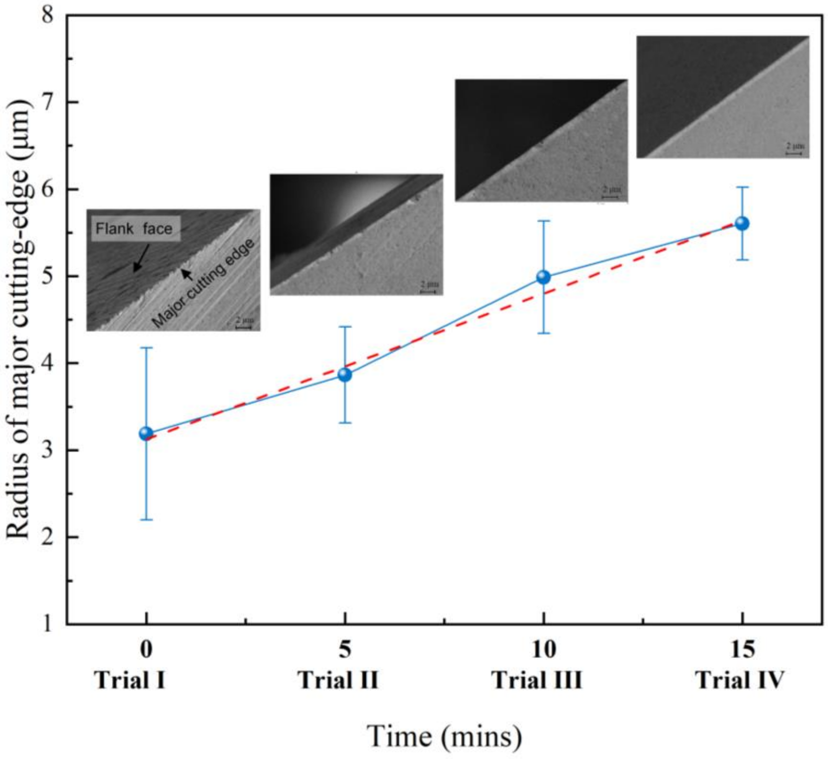


Fig.4 The influence of polishing time on cutting-edge radius

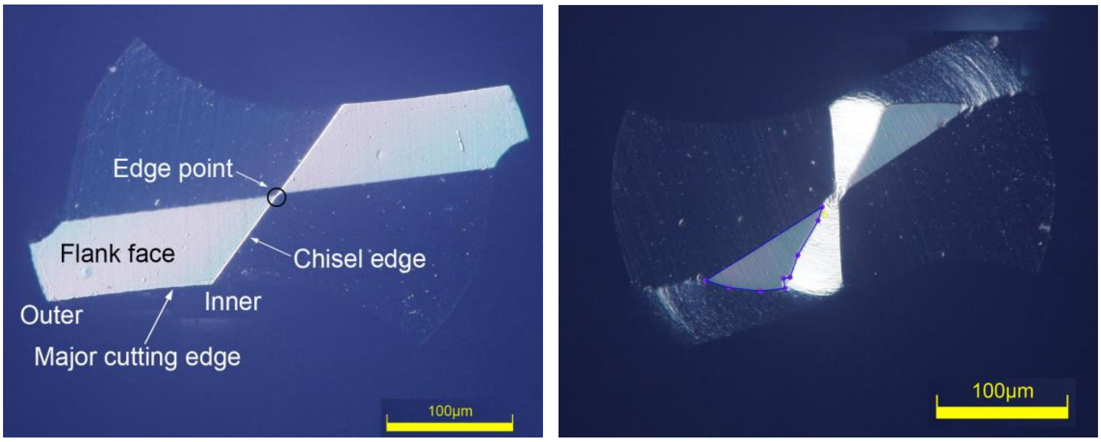
4.2 Drilling experimental analysis

4.2.1 Microdrill wear

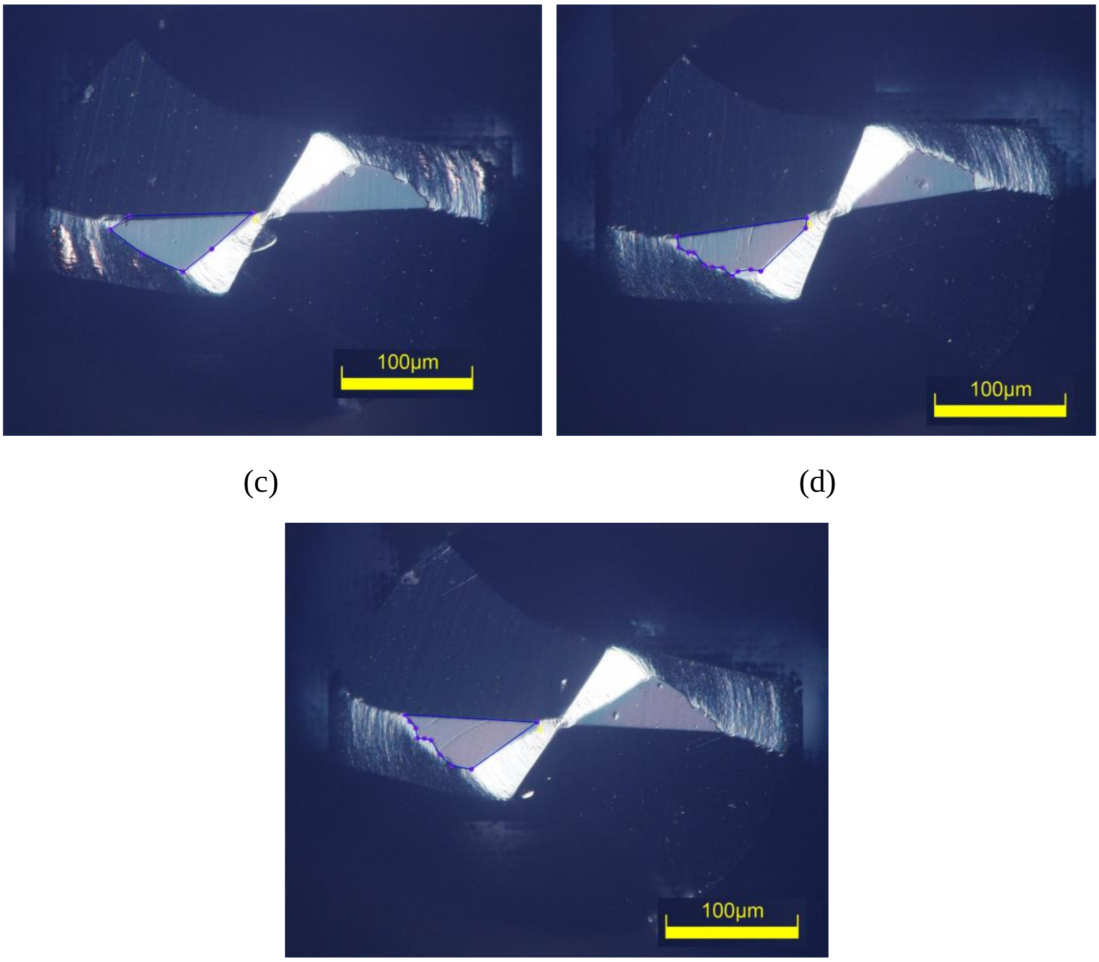
The wear of micro-drill during cutting results in the loss of cutting-edge sharpness and increase of drilling force and temperature, thereby affecting the quality of the hole [33]. And the remaining area of flank face is adopted to evaluate the microdrill wear. Fig.5 show the wear topography of the flank face after drilling 2000 holes. Maximum wear was observed at the outer edge of the major cutting-edge. The outer edge of the major cutting-edge experiences more severe wear because the outer edge of the major cutting-edge has a higher linear velocity than its inner edge. It is noteworthy that the edge point becomes dull after drilling, which affects the hole position accuracy and this aspect is discussed in more details in the next section.

The evolution of unworn area with different trials are depicted in Fig.6. This illustration clearly highlights a significant increase in the unworn area of the micro-drill in trial II when compared to the micro-drill in trial I. As the edge radius was progressively increased, the unworn area showed a gradual decrease in trial III and IV. This observation suggests that the wear of the micro-drill in trial II was comparatively lower.

However, it's important to note that if the processing time is too long, the radius of cutting-edge becomes excessively large, which was increased from to 3.8 μm (trial II) to 5.6 μm (trial IV). An excessively large cutting-edge increases the cutting resistance, which leads to severe wear. Therefore, selecting a proper edge preparation time can provide a micro-drill with optimal life [34].



(a) (b)



(c) (d)

(e)

Fig.5 Wear topography of flank face (a) Illustraion of Micro-drill structure, (b) Micro-drill of trial I after drilling 2000 holes, (c) Micro-drill of trial II after drilling 2000 holes, (d) Micro-drill of trial III after drilling 2000 holes, (e) Micro-drill of trial IV after drilling 2000 holes

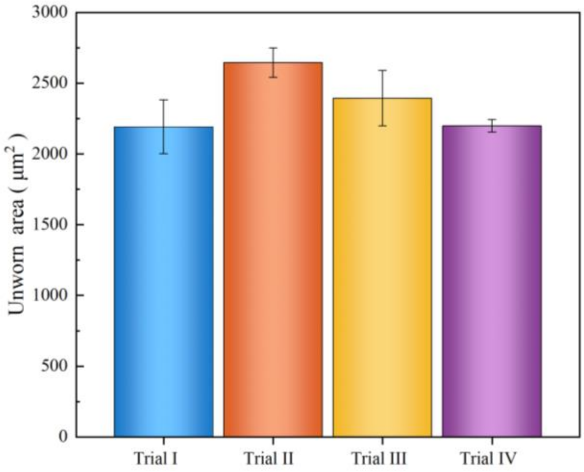


Fig.6 Statistics of unworn area in different trial

4.2.2 Hole position accuracy

The hole position accuracy is an important evaluation criterion for drilling quality. Fig.7 show the CPK statistics of 2000 holes (above the bar graph) to highlight the hole position accuracy of different trials. Besides, holes desperation is shown above the bar chart which represents position of every hole far from the theory drill center. It can be observed that the hole position accuracy improves significantly in trial II, III and IV. Especially, the drilling holes are dispersion in the trial I . When the micro-drill is worn out, the dulled edge point slides when encountering the PCBs, resulting in a decrease in hole position accuracy. Thus, the micro-drills with cutting-edge preparation exhibit enhanced wear resistance, thus achieving superior hole position accuracy. This study shows that the hole position accuracy does not decrease with the increase of cutting-edge preparation time, its' underlying mechanism remains unclear temporary. Because other factors such as drilling process parameters, diameter, cutting chip clogging, etc., can also influence the hole position accuracy [10].

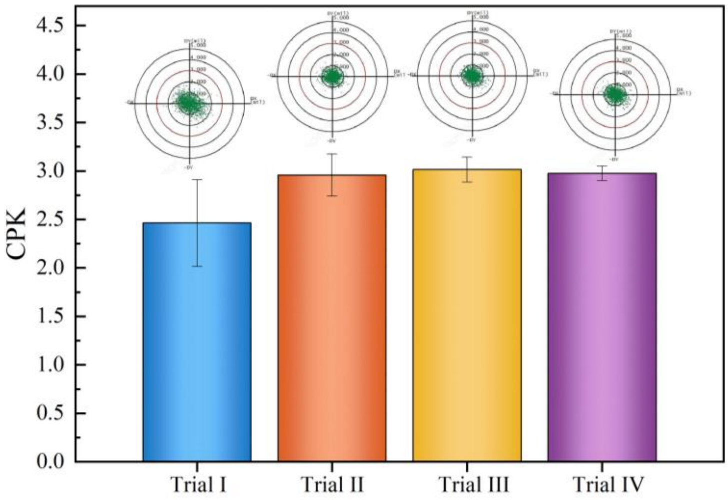


Fig.7 The hole position accuracy of different trials

4.2.3 Nail heads

The nail head, defined as the ratio of the thickness of the copper foil after drilling to its original thickness, is an important parameter to consider, as a large nail head can pose a risk of insulation layer breakdown [35]. Generally, the nail head ratio of under 1.5 is acceptable [1]. The boxplot of nail head of different trials are shown in Fig.8. It can be seen that the micro-drill of trial I exhibit the highest nail head, as well as the data shows high dispersion. And the nail head of trial II, III and IV significantly and the data also show less dispersion compared to trial I. The micro-drill of trial II show the lowest nail head value and it is also the only group that meets the requirement of a nail head of less than 1.5. This means that proper cutting-edge preparation can extend the service life of the micro-drill to more than 2000 holes.

The nail head value gradually increases with the growth of edge preparation time. The main cause of nail head formation is the blunting of cutting-edges. A sharp cutting-edge cut the copper foil by shearing action and when it becomes blunt, the copper foil deforms mainly by extrusion [36]. In addition, the large cutting-edge radius increases the temperature in the cutting region, causing the resin to soften. As a result, the copper foil extends to both sides to form a nail head. Therefore, the larger radius of cutting-edge leads to a larger nail head value.

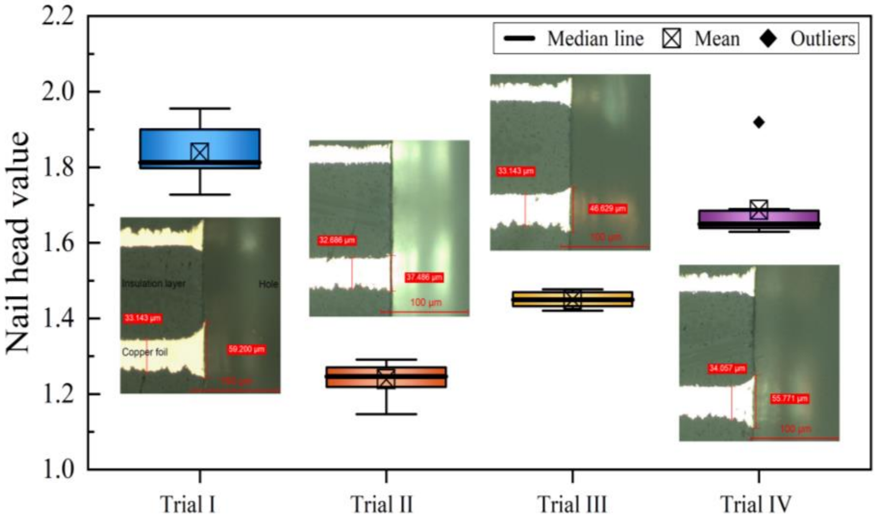
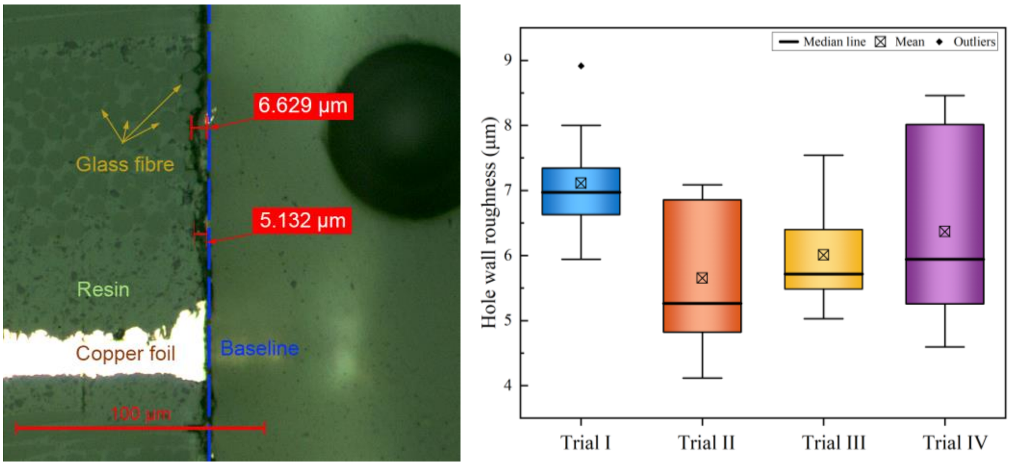


Fig.8 The nail head of different trials

4.2.4 Hole wall roughness

Fig.9 show a typical topography of hole wall roughness in different trials, where the distance between the deepest defect and the baseline was measured to characterize the hole wall roughness $R_{\max}$. By comparing a large number of slice images, it is found that the highest hole wall roughness usually occurs in the insulation layer that consists of resin and glass fiber as shown in Fig.9 (a). The formation mechanism of hole wall roughness was explained as that the cutting-edge becomes blunt, the cutting ability decreases, the glass fiber deformation process changes from shear to extrusion, which results in the dropping of glass fiber and it leaves notches behind [37]. Moreover, the linear expansion of resin is higher than copper [38] so the resin expands much larger than the copper on heating during cutting. However, the expanded resin gets cut off. After drilling is completed, the material shrinks which results in the increase of hole wall roughness. In summary, both of these mechanisms contribute to an increased hole wall roughness.

The statistic of hole wall roughness in different trials are shown in Fig.9 (b). It can be seen that the hole wall roughness $R_{\max}$ reduces significantly after the cutting-edge preparation. This is because the cutting-edge preparation reduces the wear of the cutting-edge during drilling.



(a) (b)

Fig.9 (a) Image of typical hole wall slice (b) The statistics of hole wall roughness in different trials

5. Conclusion

This research investigates the feasibility of using a novel Shear thickening polishing (STP) technique for fine processing of micro-drills as an effort to improve tool life and obtain better drilling performance during hole making on composite materials of electronic PCBs. Based on the comprehensive discussions made in the paper, the following conclusions may be summarised:

(i) The STP technique effectively removes grinding burrs and chipping on the cutting-edge, and this in turn improves the cutting-edge radius from being sharp to smooth. Increasing the STP processing time from 0 to 15 minutes increased the edge radius from 3.2 μm to 5.6 μm and this contribute positively to the performance of the micro-drill.

(ii) The cutting-edge preparation significantly improves drilling quality by removing burrs and chippings and avoiding excessive tool wear. The micro-drill edge preparation for 5 minutes showed improved hole position accuracy (CPK value of 2.96, reduced head nail value of 1.2, and a decrease in the average hole wall roughness of 5.7 μm.

(iii) An excessive edge radius can lead to rapid wear, resulting in decreased cutting ability and drilling quality, such as the edge point slipping during positioning and decreased hole position accuracy. The wear of the cutting-edge causes material removal to transition from shear fracture to extrusion, and the temperature rise softens the resin in the PCB. As a result, the copper foil expands into the insulation layer, causing the head nail value to increase, and the glass fibers drop out from the insulation layer, causing the hole wall roughness to increase.

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